Attorney Docket No. 3123-526
Express Mail No. EV 338035413 US

LONGITUDINAL MEDIA WITH SOFT UNDERLAYER AND PERPENDICULAR WRITE HEAD

Cross-Reference to Related Applications

This application claims priority from U.S. Provisional Patent Application No. 60/424,533, filed November 7, 2002, entitled "Longitudinal Media with Soft Underlayer and Shielded Pole Writer," which is incorporated herein by reference in its entirety.

Background of the Invention

1. Field of the Invention

The present invention relates to improved longitudinal (horizontal) magnetic recording media and recording devices incorporating the media. In particular, the present invention relates to longitudinal recording media having a magnetic recording layer and a magnetically soft underlayer (SUL). The longitudinal recording media can advantageously be used with a perpendicular type of write head, such as a shielded pole write head, to achieve a high areal density.

2. Description of Related Art

Thin film magnetic recording media are composed of multiple layers, including one or more magnetic recording layers, disposed on a substrate. Typically, the magnetic recording layer includes small magnetic grains that have an easy magnetization axis that is magnetically oriented longitudinally (i.e., in plane) with respect to the layer.

The areal density of longitudinal magnetic recording media has been increasing at a compounded growth rate of about 60% per year and areal densities as high as 100 Gbit/in^2 have been demonstrated. Scaling longitudinal recording media to higher areal densities requires smaller magnetic grains. However, as the grain size is reduced, thermal fluctuations can cause the magnetic domains to “flip”, causing a loss of

magnetization over a period of time. Higher coercivity media and an increased track density (tracks per inch, or TPI) can mitigate this problem. However, the large write head gaps that are needed for good overwrite of high coercivity media lead to excessive fringing, negatively affecting the data written on adjacent tracks. The large write head gaps also reduce the write field gradient and thus lead to increased transition jitter (a component of noise) and the requirement of large track width parameters, decreasing the obtainable areal density.

Longitudinal magnetic recording media with soft magnetic layers have been described in the art. U.S. Patent No. 5,041,922 by Wood et al. discloses a longitudinal magnetic recording medium that includes a hard magnetic layer and a magnetically saturable, high permeability, low coercivity (soft) magnetic layer. During signal reproduction (reading), the bias flux from the read transducer forms a saturation zone in the saturable layer that directs signal flux between the medium and the transducer.

U.S. Patent Nos. 5,176,965 and 5,431,969 both by Mallary disclose a magnetic medium for longitudinal recording. The medium includes a thin magnetic image underlayer, a magnetic recording layer and a non-magnetic buffer layer disposed between the image underlayer and the magnetic recording layer. Charges located in the magnetic layer induce virtual magnetic images of opposite charge in the underlying magnetic image underlayer. The virtual image charges reduce the fringing effect in adjacent tracks during read operations. It is disclosed that the magnetic image layer can be magnetically soft, semi-soft or semi-hard.

In addition to longitudinal recording, perpendicular (vertical) magnetic recording media have been proposed as a way to increase areal densities. Perpendicular magnetic recording media include a magnetic recording layer having an easy magnetization axis that is perpendicular to the layer. A perpendicular write head, such as a monopole write head or a shielded pole write head, is utilized to magnetize the grains in the perpendicular recording layer. Examples of perpendicular recording media and perpendicular write heads are disclosed in U.S. Patent No. 4,656,546 by Mallary and U.S. Patent No. 4,748,525 by Perlov.

Among the desirable properties for the magnetic recording layer is a high coercivity. Coercivity is a measure of the magnetization field that must be applied to reduce the remnant magnetization to zero, i.e., to reverse the direction of magnetization. A high coercivity assures that the magnetic layer will have a high resistance to demagnetization by stray magnetic fields and will have good thermal stability. However, high coercivity media also require a high field strength to reverse the direction of magnetization, making the media difficult to write.

Therefore, there is a need for a longitudinal recording medium having an increased coercivity and an associated read/write device effective to form a strong field gradient across the magnetic material. There is also a need for a longitudinal recording medium having a high areal density that is capable of producing an acceptably high signal-to-noise ratio (SNR).

Brief Summary of the Invention

The present invention is directed to a magnetic recording device that includes a longitudinal recording layer that is effectively disposed within the write gap of a perpendicular write head, such as a shielded pole write head. This combination provides a high write field gradient and reduced transition width. As a result, fewer magnetic grains per bit are required in the magnetic recording layer to achieve an acceptable signal-to-noise ratio, thereby increasing the obtainable areal density. The magnetic recording layer can also have an increased coercivity for greater thermal stability. A magnetically soft underlayer imparts a keeper effect and allows for the use of a thicker magnetic recording layer.

According to one embodiment of the present invention, a magnetic recording device is provided. The magnetic recording device includes a perpendicular write head having a write pole including a write pole tip and a return pole. A recording medium including a longitudinal magnetic recording layer and a soft magnetic underlayer is disposed in relation to the perpendicular write head to place the magnetic recording layer within an effective write gap formed by the perpendicular write head and the underlayer during operation of the magnetic recording device. The perpendicular write

head can be, for example, a shielded pole write head or a monopole write head. The magnetic recording medium can also include a non-magnetic spacer layer disposed between the longitudinal magnetic recording layer and the soft magnetic underlayer. The soft magnetic underlayer can have a magnetic coercivity of not greater than about 5 Oersteds (Oe) and can have a magnetic permeability of at least about 50. The soft magnetic underlayer preferably has a thickness sufficient to prevent saturation of the underlayer by the perpendicular write head during operation of the device. For example, the soft magnetic underlayer can have a thickness of from about 30 nanometers to about 200 nanometers.

According to another embodiment of the present invention, a magnetic recording device is provided that includes a shielded pole write head having a write pole tip and a write shield. A magnetic recording medium is disposed under the shielded pole write head, where the magnetic recording medium includes a soft magnetic underlayer having a permeability of at least about 50, a non-magnetic spacer layer disposed over the underlayer and a longitudinal magnetic recording layer disposed over the non-magnetic spacer layer.

According to another embodiment of the present invention, a magnetic recording medium is provided. The magnetic recording medium includes a substrate, an underlayer disposed over the substrate where the underlayer has a magnetic permeability of at least about 50, a non-magnetic spacer layer disposed over the underlayer and having a thickness of not greater than about 40 nanometers, and a longitudinal recording layer disposed over the non-magnetic spacer layer where the longitudinal recording layer has a coercivity of at least about 4000 Oe.

According to another embodiment, a method for writing data to a longitudinal recording layer is provided. The method includes the steps of providing a write head having a write pole and a return pole, disposing a longitudinal recording layer proximal to the write head, where the recording layer has a soft magnetic underlayer disposed under the recording layer, moving the longitudinal recording layer relative to the write head and generating a magnetic flux between the write pole tip and the soft magnetic underlayer. The magnetic flux is applied substantially perpendicular to the longitudinal

recording layer and the magnetic flux is directed to the return pole by the soft magnetic underlayer.

Brief Description of the Drawings

Fig. 1 illustrates a top or plan view of one embodiment of a disk drive.

Fig. 2 illustrates a schematic side view of a write head adjacent to a longitudinal recording medium according to the prior art.

Fig. 3 illustrates a schematic side view of a longitudinal magnetic recording medium and perpendicular read/write head (shielded pole write head) according to an embodiment of the present invention.

Fig. 4 illustrates a schematic side view of a longitudinal magnetic recording medium and perpendicular read/write head (monopole write head) according to an embodiment of the present invention.

Fig. 5 illustrates a schematic side view of a longitudinal magnetic recording medium and a perpendicular write head (shielded pole write head) according to an embodiment of the present invention.

Fig. 6 illustrates a cross-sectional view of a longitudinal recording medium according to an embodiment of the present invention.

Fig. 7 illustrates perpendicular and longitudinal magnetic fields as a function of longitudinal position generated by a shielded pole write head and a ring write head.

Fig. 8 illustrates the effective switching field strength as a function of longitudinal position for a shielded pole write head and a ring write head.

Fig. 9 illustrates the normalized effective field gradient as a function of effective switching field strength for a shielded pole write head and a ring write head.

Fig. 10 illustrates the normalized gradient as a function of switching field strength for various shielded pole write heads and a ring write head.

Detailed Description of the Invention

The present invention is directed to a magnetic recording medium and a magnetic recording device, wherein the magnetic recording medium includes a longitudinal magnetic recording layer. As used herein, a longitudinal magnetic recording layer is a magnetic recording layer where the magnetic grains have an easy magnetization axis that is oriented substantially parallel to the plane of the layer. The magnetic recording medium can be, for example, a magnetic tape or a magnetic hard disk, and in a preferred embodiment is a magnetic hard disk for use in a disk drive.

Fig. 1 illustrates one embodiment of a disk drive **110**. The disk drive **110** generally includes a base plate **112** and a cover (not shown) that may be disposed on the base plate **112** to define an enclosed housing or space for the various disk drive components. The disk drive **110** includes one or more data storage disks **114** of any appropriate computer-readable data storage media. Typically, both of the major surfaces of each data storage disk **114** include a plurality of concentrically disposed tracks for data storage purposes. Each disk **114** is mounted on a hub or spindle **116**, which in turn is rotatably interconnected with the disk drive base plate **112** and/or cover. Multiple data storage disks **114** are typically mounted in vertically spaced and parallel relation on the spindle **116**. Rotation of the disk(s) **114** is provided by a spindle motor **118** that is coupled to the spindle **116** to simultaneously spin the data storage disk(s) **114** at an appropriate rate.

The disk drive **110** also includes an actuator arm assembly **120** that pivots about a pivot bearing **122**, which in turn is rotatably supported by the base plate **112** and/or cover. The actuator arm assembly **120** includes one or more individual rigid actuator arms **124** that extend out from near the pivot bearing **122**. Multiple actuator arms **124** are typically disposed in vertically spaced relation, with one actuator arm **124** being provided for each major data storage surface of each data storage disk **114** of the disk drive **110**. Other types of actuator arm assembly configurations could be utilized as well, such as an "E" block having one or more rigid actuator arm tips or the like that cantilever from a common structure. In any case, movement of the actuator arm assembly **120** is provided by an actuator arm drive assembly, such as a voice coil motor

126 or the like. The voice coil motor **126** is a magnetic assembly that controls the operation of the actuator arm assembly **120** under the direction of control electronics **128**. Any appropriate actuator arm assembly drive type may be utilized by the disk drive **110**, including a linear drive (for the case where the actuator arm assembly **120** is interconnected with the base plate **112** and/or cover for linear movement versus the illustrated pivoting movement about the pivot bearing **122**) and other types of rotational drives.

A load beam or suspension **130** is attached to the free end of each actuator arm **124** and cantilevers therefrom. Typically, the suspension **130** is biased generally toward its corresponding disk **114** by a spring-like force. A slider **132** is disposed at or near the free end of each suspension **130**. What is commonly referred to as the read/write head (e.g., transducer) is appropriately mounted on the slider **132** and is used in disk drive read/write operations.

The head on the slider **132** may utilize various types of read sensor technologies such as anisotropic magnetoresistive (AMR), giant magnetoresistive (GMR), tunneling magnetoresistive (TuMR), other magnetoresistive technologies, or other suitable technologies. AMR is due to the anisotropic magnetoresistive effect with a normalized change in resistance ($\Delta R/R$) of 2 – 4%. GMR results from spin-dependent scattering mechanisms between two (or more) magnetic layers. The typical use in recording heads is the spin valve device that uses a pinned magnetic layer and a free layer to detect external fields. The normalized change in on-wafer resistance is typically 8 – 12%, but can be as large as 15 – 20% when used with specular capping layers and spin-filter layers. TuMR is similar to GMR, but is due to spin dependent tunneling currents across an isolation layer. The typical embodiment includes a free layer and a pinned layer separated by an insulating layer of Al_2O_3 with the current flowing perpendicular to the film plane, producing normalized change in resistance of 12 – 25%. The term magnetoresistive is used in this application to refer to all these types of magnetoresistive sensors and any others in which a variation in resistance of the sensor due to the application of an external magnetic field is detected. The read/write head of the present invention is discussed in further detail below.

The biasing forces exerted by the suspension **130** on its corresponding slider **132** moves the slider **132** in the direction of its corresponding disk **114**. Typically, this biasing force is such that if the slider **132** were positioned over its corresponding disk **114**, without the disk **114** being rotated at a sufficient velocity, the slider **132** would be in contact with the disk **114**.

The head on the slider **132** is connected to a preamplifier **133**, which is interconnected with the control electronics **128** of the disk drive **110** by a flex cable **134** that is typically mounted on the actuator arm assembly **120**. Signals are exchanged between the head and its corresponding data storage disk **114** for disk drive read/write operations. In this regard, the voice coil motor **126** is utilized to pivot the actuator arm assembly **120** to simultaneously move the slider **132** along a path **136** and “across” the corresponding data storage disk **114** to position the head at the desired/required radial position on the disk **114** (i.e., at the approximate location of the correct track on the data storage disk **114**) for disk drive read/write operations.

When the disk drive **110** is not in operation, the actuator arm assembly **120** is pivoted to a “parked position” to dispose each slider **132** generally at or beyond a perimeter of its corresponding data storage disk **114**, but in any case in vertically spaced relation to its corresponding disk **114**. This is commonly referred to in the art as being a dynamic load/unload disk drive configuration. In this regard, the disk drive **110** includes a ramp assembly **138** that is disposed beyond a perimeter of the data storage disk **114** to typically both move the corresponding slider **132** vertically away from its corresponding data storage disk **114** and to also exert somewhat of a retaining force on the actuator arm assembly **120**. Any configuration for the ramp assembly **138** that provides the desired “parking” function may be utilized. The disk drive **110** could also be configured to be of the contact start/stop type, where the actuator arm assembly **120** would pivot in a direction to dispose the slider(s) **132** typically toward an inner, non-data storage region of the corresponding data storage disk **114**. Terminating the rotation of the data storage disk(s) **114** in this type of disk drive configuration would then result in the slider(s) **132** actually establishing contact with or "landing" on its corresponding data storage disk **114**, and the slider **132** would remain on the disk **114** until disk drive operations are re-initiated.

The slider **132** of the disk drive **110** may be configured to "fly" on an air bearing during rotation of its corresponding data storage disk(s) **114** at a sufficient velocity. The slider **132** may be disposed at a pitch angle such that its leading edge is disposed further from its corresponding data storage disk **114** than its trailing edge. The read/write head would typically be incorporated on the slider **132** generally toward its trailing edge since this is positioned closest to its corresponding disk **114**. Other pitch angles/orientations could also be utilized for flying the slider **132**.

Referring to Fig. 2, a write head **200** and longitudinal recording medium **201** (e.g., a data storage disk) according to the prior art are illustrated. The write head **200** (commonly referred to as a ring head) floats above the surface of a longitudinal recording layer **214** of a magnetic recording medium **201** as the magnetic recording medium moves in the direction of arrow **216** during operation. It will be appreciated by those skilled in the art that the magnetic recording medium **201** can include other layers (not illustrated) such as underlayers and seedlayers.

The longitudinal write head **200** includes first and second write poles **204** and **206**, which define a write gap **212** between the poles. When an electric current is passed through the coils **208**, a magnetic flux **210** is developed in the write gap **212**. Changing the direction of the current in the coils **208** changes the polarity of the magnetic flux **210** in the gap **212**. During operation, the recording head **200** is passed above and in close proximity to the longitudinal recording layer **214**. The fringe portion of the flux **210** magnetizes the magnetic grains in the recording layer **214** in a longitudinal direction. It is noteworthy that the magnetic recording layer **214** is not disposed within the write gap **212** of the write head **200**, but is disposed in proximity to the fringing field of the magnetic flux **210**. Thus, the polarity of the magnetic domains in the magnetic recording layer **214** is switched by the fringing field of the flux **210** generated between the poles **204** and **206**. This results in a relatively low field gradient and difficulty writing to a recording layer **214** having a high coercivity. Increasing the strength of the magnetic field in the gap **212** (e.g., by increasing the size of the gap **212**) can result in off-track fringing signals, interfering with adjacent tracks on the recording layer **214**, thereby decreasing the obtainable areal density for the recording medium **201**.

Fig. 3 illustrates a schematic side view of a longitudinal magnetic recording medium in combination with a perpendicular write head, specifically a shielded pole write head, according to the present invention. A shielded pole write head is disclosed in U.S. Patent No. 4,656,546 by Mallary, which is incorporated herein by reference in its entirety. A shielded pole write head is also disclosed in commonly-owned U.S. Patent Application Serial No. 10/365,287, filed on February 12, 2003 and entitled "Floating Down Stream Perpendicular Write Head Shield," which is also incorporated herein by reference in its entirety.

Referring to Fig. 3, the relevant portions of a read/write head **300** are illustrated adjacent to a portion of a magnetic recording medium **302** that is moving relative to the head **300** in a direction shown by arrow **304.** The read/write head **300** includes a read portion **306** for detecting bits in the magnetic recording layer **324** and a write portion **308** for writing bits in the magnetic recording layer **324.**

The read portion **306** includes a first shield **312** and a second shield **310.** Disposed between the shields **310** and **312** is a magneto restrictive (MR) sensor stripe **314**. The MR sensor stripe **314** may utilize the various MR sensor technologies, and in one embodiment a GMR sensor is employed.

The write portion **308** of the read/write head **300** includes a write yoke **316** connected at one end to a downstream return pole, in this case a write shield **321**. Wrapped around the write yoke **316** are a plurality of pancake-shaped electrically conductive coils **318**. A write pole **320** is constructed parallel to the second read shield **310** and in contact at one end thereof with the write yoke **316**. The write pole **320** terminates at an opposite end with a write pole tip **322**, which has a reduced cross-section as compared to the remainder of the write pole **320**. As compared to a longitudinal write head (Fig. 2), the write pole tip **322** is relatively thin to minimize skew problems and preferably has a trapezoidal shape. The end of the write pole tip **322** is generally vertically aligned with the ends of the read shields **310** and **312** and the MR sensor stripe **314,** and is located extremely close to the planar upper surface of the magnetic recording medium **302**. As illustrated in Fig. 3, the write shield **321** is downstream from the write pole **320**.

It will be appreciated that an extra coil **319** (a bucking coil) may be used between the write pole **320** and the second read shield **310** to reduce flux coupling. When a bucking coil **319** is utilized, it is preferred that the number of turns in the bucking coil **319** is equal to or less than the number of turns in the write coil **318**. Flux coupling between the second read shield **310** and the write pole **320** can also be reduced by wrapping the write coil **318** around the write pole **320**, thus forming a solenoidal coil. However, the use of a large write pole to read shield gap **332** can reduce flux coupling without the use of a bucking coil. A large write gap **323** and a large area write shield **321** increase the write field strength under the write pole tip **322**. A small write gap **323** between the write pole **320** and the write shield **321** reduces the field strength but increases the field gradient.

The magnetic recording medium **302** includes a longitudinal magnetic recording layer **324** adjacent to the read/write head **300** and a soft underlayer (SUL) **328** on the opposite side of the magnetic recording layer **324** from the read/write head **300**. A non-magnetic spacer layer **326** is disposed between the recording layer **324** and the underlayer **328**. As is discussed in more detail below, the magnetic recording layer **324** is preferably a hard magnetic material while the SUL **328** is preferably a soft magnetic material. A soft magnetic material generally has a high permeability and a low coercivity, whereas a hard magnetic material has a low permeability and a high coercivity.

During operation, the magnetic flux **330** from the write pole tip **322,** in the region of high field gradient, passes through the magnetic recording layer **324** in a direction that is slanted with respect to the perpendicular axis of the layer and into the SUL **328.** As is discussed in more detail below, the magnetic flux **330** in the region of high field gradient includes a longitudinal component that is sufficient to switch longitudinally oriented grains in the longitudinal magnetic recording layer **324.** That is, although the perpendicular component of the magnetic flux is greater than the longitudinal component, the longitudinal component is sufficient to switch magnetic grains in the magnetic recording layer. The SUL **328** provides a high permeability pathway for the flux **330** to return to the write shield **321.** In this manner, magnetic recording layer **324** is disposed within the write gap of the read/write head **300.** When the current applied to

the coils **318** changes polarity, the flux passes from the shield **321**, through the underlayer **328** and to the write pole tip **322**.

The perpendicular write head can also be a monopole write head. Referring to Fig. 4, a monopole read/write head and longitudinal recording medium are illustrated. The relevant portions of a read/write head **400** are illustrated adjacent to a portion of a magnetic recording medium **402** that is moving relative to the head **400** in a direction shown by arrow **404**. The read/write head **400** includes a read portion **406** and a write portion **408**, that together utilize a shared shield **410**, the shared shield **410** being upstream from the write pole **420** and functioning as a return pole. The read portion **406** includes a first shield **412** and the shared shield **410**. Disposed between the shields **410** and **412** is a magneto restrictive (MR) sensor stripe **414**. The MR sensor stripe **414** may utilize the various MR sensor technologies, and in one embodiment a GMR sensor is employed.

The write portion **408** of the read/write head **400** includes a write yoke **416** connected at one end to the shared shield **410**. Wrapped around the write yoke **416** are a plurality of pancake-shaped electrically conductive coils **418**. A write pole **420** is constructed parallel to the shared shield **410** and in contact at one end thereof with the write yoke **416**. The write pole **420** terminates at an opposite end with a write pole tip **422**, which has a reduced cross-section as compared to the remainder of the write pole **420**. The write pole tip **422** is relatively thin to minimize skew problems and preferably has a trapezoidal shape. The end of the write pole tip **422** is generally vertically aligned with the ends of the shields **410** and **412** and the MR sensor stripe **414,** and is located extremely close to the planar upper surface of the magnetic recording medium **402**.

The magnetic recording medium **402** includes a longitudinal magnetic recording layer **424** adjacent to the read/write head **400** and a soft underlayer (SUL) **428** on the opposite side of the magnetic recording layer **424** from the read/write head **400**. A non-magnetic spacer layer **426** is disposed between the recording layer **424** and the underlayer **428**. The magnetic recording layer **424** is preferably a hard magnetic material while the SUL **428** is preferably a soft magnetic material.

During operation, the magnetic flux **430** from the write pole tip **422**, in the region of high field gradient, passes through the magnetic recording layer **424** in a direction

that is slanted with respect to the perpendicular axis of the layer and into the SUL **428.** The SUL **428** provides a high permeability pathway for the flux **430** to return to the shield **410.** In this manner, magnetic recording layer **424** is effectively disposed within the write gap of the read/write head **400.** When the current applied to the coils **418** changes polarity, the flux passes from the shield **410**, through the underlayer **428** and to the write pole tip **422**.

A more detailed view of a write pole, write shield and magnetic recording medium, such as that illustrated in Fig. 3, is illustrated in Fig. 5. As illustrated in Fig. 5, the recording medium **502** moves in the direction of arrow **504** relative to the write pole **520** and write shield **510**. In the embodiment illustrated in Fig. 5, the write coil **518** is wrapped around the write pole **520** forming a solenoidal coil. The flux **530** generated by the write pole tip **522** at the end of the write pole **520** extends through the magnetic recording layer **524** in the region of high field gradient in a direction that is slanted to the perpendicular axis of the magnetic recording medium **502** and into the soft underlayer **528.** The soft underlayer **528** is of a sufficient thickness and permeability that the soft underlayer does not saturate and the flux **530** is directed back to the write shield **510**. A non-magnetic spacer layer **526** disposed between the soft underlayer **528** and the magnetic recording layer **524** reduces the loss of high frequency read signals.

The thickness (d_1) of the non-magnetic spacer layer **526** is preferably selected such that the distance (d_2) from the center of the longitudinal magnetic recording layer **524** to the top surface **529** of the soft underlayer **528** is about equal to the distance (d_3) from the center of the longitudinal magnetic recording layer **524** to the pole tip **522**, a distance referred to herein as the magnetic spacing ($d_2 \approx d_3$).

Further, the width (d_{gap}) of the gap **523** from the write pole **520** to the write shield **510** is preferably selected to be about equal to the distance (d_4) from the write pole **520** to the top of the soft underlayer **528**. ($d_2 + d_3 = d_4 \approx d_{gap}$). More specifically, d_{gap} is preferably no more than about twice as large and no smaller than twice as small as d_4. This configuration yields an acceptable trade-off between write field strength and write field gradient. In one preferred embodiment, d_{gap} is from about 40 to about 80 nanometers.

In accordance with the foregoing, the thickness of the non-magnetic spacer layer (d_1) is preferably from about 10 to 25 nanometers. The distance from the top of the SUL to the center of the longitudinal recording layer (d_2) is preferably from about 13 to 31 nanometers. The distance d_3 from the center of the recording layer to the pole tip during operation of the recording device (the magnetic spacing) is preferably from about 10 to about 30 nanometers and is preferably about equal to d_2 , and more specifically is preferably no greater than about 20% larger or smaller than d_2. In one embodiment, both d_2 and d_3 are each from about 15 nanometers to about 30 nanometers.

Utilizing the foregoing criteria according to the present invention, the longitudinal magnetic recording layer **524** is effectively disposed within the write gap of the write head. It has been found that although the primary write head field is perpendicular to the recording layer, the field also has a longitudinal component that is sufficient to switch the longitudinally oriented magnetic grains in the recording layer. The polarity of the longitudinal field component can be switched by switching the polarity of the perpendicular component, i.e., by changing the polarity of the current in the coils.

Fig. 6 illustrates a cross-sectional view of a longitudinal magnetic recording medium, namely a hard disk, in accordance with the present invention. The medium includes a rigid substrate **602** for supporting the overlying layers. The substrate **602** can be fabricated from a variety of materials such as aluminum or an aluminum alloy coated with nickel phosphorous (NiP), or a glass or glass-ceramic. A seedlayer **604** or other intermediate layers known to those skilled in the art can be provided, such as to enhance the crystallographic properties of the magnetic layers disposed thereon.

The magnetic recording medium **600** includes a longitudinal magnetic recording layer **610** and a soft underlayer **606**, with a non-magnetic spacer layer **608** disposed between the recording layer **610** and the soft underlayer **606**. The spacer layer **608** is adapted to reduce the loss of high frequency read signals without substantially degrading the write field strength or the write field gradient. Typically, the spacer layer **608** will have an average thickness of not greater than about 40 nanometers, more preferably not greater than about 20 nanometers. The spacer layer **608** preferably has a thickness of at least about 10 nanometers and in one embodiment, the average

thickness is from about 10 to about 25 nanometers. The non-magnetic spacer layer can be fabricated from, for example, Cr, Ta, NiAl, or other alloys that result in good growth properties of the magnetic hard layer.

The soft underlayer **606** is essential to obtain a high write field and a strong write field gradient, leading to an increased areal density and other improved properties in the longitudinal recording layer **610**. Unlike soft underlayers disclosed in the prior art in connection with longitudinal layers, the soft underlayer **606** does not saturate during write operations. During read operations, the soft underlayer **606** provides a partial keeper effect that enhances magnetic stability while not absorbing all of the read flux because of the spacer layer **608**. The soft underlayer **606** can selectively absorb the low frequency component of the read flux, thereby narrowing the pulse width (PW_{50}) and reducing the dynamic range requirement of the read transducer.

The soft underlayer **606** can be fabricated from a variety of soft magnetic materials such as NiFe, FeTaC or CoZrNb. Preferably, the soft underlayer has a magnetic permeability (μ) of at least about 50, even more preferably at least about 100 and even more preferably at least about 500. Further, the coercivity (H_c) of the soft underlayer should be relatively low and in one embodiment is not greater than about 5 Oe, more preferably not greater than about 2 Oe. The soft underlayer preferably has a thickness of at least about 30 nanometers, more preferably at least about 50 nanometers, and even more preferably at least about 100 nanometers. In one embodiment, the soft underlayer has a thickness of from about 30 nanometers to about 200 nanometers, such as from about 100 to about 200 nanometers. The thickness and magnetic properties of the soft underlayer should be sufficient such that the soft underlayer does not saturate during write operations.

The longitudinal magnetic recording layer **610** has an easy magnetization axis that is oriented parallel with the surface of the recording layer. Useful materials for the magnetic recording layer **610** include cobalt-based alloys, such as those having a hexagonal close packed (hcp) crystal structure. Cobalt can be alloyed with elements such as chromium (Cr), platinum (Pt), boron (B), niobium (Nb), tungsten (W) and tantalum (Ta). For example, the magnetic recording layer **610** can include cobalt

alloyed with chromium, platinum and boron (CoCrPtB). The magnetic recording layer **610** preferably has an average thickness of not greater than about 15 nanometers, such as from about 7 to about 12 nanometers. It will be appreciated by those skilled in the art that multiple magnetic recording layers can be utilized. Longitudinal anisotropy can be induced in the longitudinal magnetic recording layer **610** by the selection of suitable alloys for the recording layer **610** and the spacer layer **608.**

The present invention enables the use of a recording medium wherein the longitudinal recording layer has a high coercivity. The use of a high coercivity longitudinal recording layer is enabled by the properties of the longitudinal switching field applied by the perpendicular write head. According to one embodiment, the longitudinal recording layer has a coercivity of at least about 4000 Oe and more preferably at least about 5000 Oe.

Simulations of a shielded pole perpendicular write head on a longitudinal magnetic recording medium having a longitudinal recording layer, a soft underlayer (SUL) and a non-magnetic spacer layer according to the present invention are illustrated in Figs. 7-10.

Fig. 7 illustrates that a large increase in writeability and normalized write field gradient can be achieved using a perpendicular write head relative to conventional longitudinal recording using a ring head. Specifically, Fig. 7 shows the calculated longitudinal magnetic field (B_{long}) and perpendicular magnetic field (B_{perp}) at a distance 15 nanometers from the pole tips for a shielded pole perpendicular write head compared to a longitudinal ring head. For the shielded pole perpendicular write head, the effective write head gap is equal to the distance from the pole tip to the upper surface of the soft underlayer (i.e., d_4 in Fig. 5) and in this case is 25 nanometers (e.g., where the magnetic recording layer is 10 nanometers thick and the spacer layer is 5 nanometers thick). The longitudinal ring head used for comparison has a write head gap of 50 nanometers and a magnetic potential asymmetry of 76%. This asymmetry arises since the total area of the bottom pole plus the read shield is much larger than the area of the write yoke. This produces a large asymmetry in the magnitude of the magnetic potentials at the pole tips. In each case, the gap field is normalized to 1.0. As

expected, the longitudinal ring head has a higher longitudinal field than the perpendicular head, but a lower perpendicular field.

However, it has been found that both the longitudinal and perpendicular field components are important for switching the polarity of magnetic grains. To account for the combined effect of the two components, the Stoner-Wolfarth switching field strength (H_{sw}) can be calculated from Equation 1:

$$H_{sw} = H_{total} \bullet [\sin(\Theta)^{2/3} + \cos(\Theta)^{2/3}]^{3/2} \qquad (1)$$

where H_{total} is the absolute value of the magnetic field and Θ is the angle between the magnetic field and the easy magnetization axis of the magnetic grain. For a field parallel to the easy magnetization axis (Θ=0), H_{sw}=H_{total}.

Because $\sin(\Theta+90) = \cos(\Theta)$, Equation 1 applies equally to perpendicular grains and circumferential grains, ignoring self demagnetization field effects. Fig. 8 illustrates the calculated Stoner-Wolfarth switching field for the same shielded pole perpendicular write head and the longitudinal ring head configurations of Fig. 7. It can be seen that the shielded pole perpendicular write head has more normalized field gradient and a higher maximum field strength. In operation, the longitudinal ring head writes on the right most slope, where the peak P2 is higher than the left-hand peak P1.

Because of the complex trade-off between the write field (switching field) strength and normalized gradient, it is useful to plot them against each other. This is illustrated in Fig. 9 for the same shielded pole write head and the ring head configurations of Figs. 7 and 8. The longitudinal ring head has two plots, corresponding to peaks P1 and P2 in Fig. 8. As is illustrated in Fig. 9, the normalized field gradient of the shielded pole perpendicular write head is high at low switching field strengths. At H_{sw}= 0.65, where the ring head has a maximum normalized gradient, the shielded pole head has a 2.8x higher gradient. Further, the peak switching field strength of the shielded pole perpendicular write head is 55% higher than the peak switching field strength of the longitudinal ring head.

The results for two other configurations of a shielded pole head are illustrated in Fig. 10 along with the curves from Fig. 9. Fig. 10 illustrates that if the non-magnetic spacer layer thickness in the longitudinal media is increased from 5 nanometers to 25 nanometers (e.g., the effective write head gap goes from 25 nanometers to 45 nanometers for a magnetic recording layer thickness of 10 nanometers), the maximum switching field for the shielded pole head becomes 82% better than for the ring head, but the maximum gradient at H_{sw}=0.65 is only 2x better.

Also illustrated in Fig. 10 are the calculated results obtained by increasing the shielded pole gap to 33 nanometers and applying –1/3 magneto-motive force (V_{SH}) to the shield. The resulting field under the shield (e.g., H_{sw}=0.55) is just below that which could erase adjacent track data with repeated passes if the media anisotropy field is optimally set at H_k=1.06H_{sw} so that write occurs at the point of maximum gradient. Under these circumstances the gradient of the shielded pole write head is 3.4x better than that of the ring head at H_{SW} =0.7. In a system in which the transition width is not limited by the magnetic grain size, this can be expected to yield up to a 5x increase in areal density. Negative V_{SH} can be optimized with a bucking coil that has fewer turns than the write coil and is located between the write pole and the second read shield (See Fig. 3). Alternatively, this can be accomplished by adjusting the distance from the write pole to the second read shield.

The foregoing combination of a longitudinal magnetic recording medium disposed in the write gap of a perpendicular write head improves the write and read processes as compared to longitudinal media utilized in combination with a longitudinal read/write head. The write field generated by the magnetic recording device of the present invention has a greater ability to switch the magnetic recording layer due to an increased field gradient and the combined effect of the horizontal and perpendicular field components. The soft underlayer provides a partial keeper effect that enhances magnetic stability while not absorbing all of the read flux. The soft underlayer selectively absorbs the low frequency component of the read back flux, narrowing the pulse width and reducing the dynamic range requirement of the read transducer.

The longitudinal media according to the present invention offers numerous advantages. When used in conjunction with a perpendicular write head, such as a shielded pole write head, the write field gradient can be increased by a factor of 3 times, enabling the writing of sharp transitions on longitudinal media. For the same normalized gradient, media having 1.5 times higher coercivity can be written. This increases the thermal stability of the media and as a result smaller grains can be used in the longitudinal magnetic recording layer, which in turn allows for smaller bit areas for a given number of grains per bit, also leading to higher areal densities. The net SNR gain can be more than 9 dB. As a result, fewer magnetic grains per bit are required for adequate SNR and an increase in areal density of up to 2 times and even up to 3 times is enabled using the same longitudinal magnetic recording layer.

While various embodiments of the present invention have been described in detail, it is apparent that modifications and adaptations of those embodiments will occur to those skilled in the art. However, it is to be expressly understood that such modifications and adaptations are within the spirit and scope of the present invention.